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CASE STUDY • POWER GENERATION • ENVIRONMENTAL AND HUMAN HEALTH EFFECTS

Environmental assessment of German electricity generation from coal-fired power plants with amine-based carbon capture

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Abstract
Background, aim, and scope One of the most important sources of global carbon dioxide emissions is the combustion of fossil fuels for power generation. Power plants contribute more than 40% of the worldwide anthropogenic CO_2 emissions. Therefore, the increased requirements for climate protection are a great challenge for the power producers. In this context a significant increase in power plant efficiency will contribute to reduce specific CO_2 emissions. Additionally, CO_2 capture and storage (CCS) is receiving considerable attention as a greenhouse gas (GHG) mitigation option. CCS allows continued use of fossil fuels with no or little CO_2 emissions given to the atmosphere. This could approve a moderate transition to a low-carbon energy generation over the next decades. Currently, R&D activities in the field of CCS are mainly concentrated on the development of capture techniques, the geological assessment of CO_2 storage reservoirs, and on economic aspects. Although first studies on material and energy flows caused by CCS are available, a broader environmental analysis is necessary to show the overall environmental impacts of CCS. The objectives in this paper are coal-based power plants with and without CO_2 capture via monoethanolamine (MEA) and the comparison of their environmental effects based on life cycle assessment methodology (LCA).
Methods This LCA study examines the environmental and human health effects of power generation of five coal-based steam power plants, which differ in the year of installation (2005, 2010, 2020), the conversion efficiency, and in the ability and efficiency to capture CO_2. For the removal of CO_2 from combustion and gasification processes in power plants, three main technology concepts exist: (1) *pre-combustion* technology, (2) *oxyfuel* combustion systems, and (3) *post-combustion* separation. As post-combustion technology shows the highest level of maturity, this study concentrates on this route, focusing on capture using monoethanolamine (MEA). The analysis regards the post-combustion retrofit of coal power plants with MEA to be a general option in 2020.
Results Material and energy flows are balanced on the level of single processes as well as for the whole process chains. The life cycle inventory clearly shows decreasing inputs and outputs according to the efficiency increase from 43% to 49% in case of the power plants without CO_2 capture. In case of the MEA plants, all inputs and emissions raise, according to the additional energy consumption, except CO_2 and sulphur dioxide. The strong decrease of SO_2 partly results from the necessary improvement of desulphurisation if MEA wash is used. The influence of up and downstream activities on the results is determined. For the MEA plants, a considerable effect of up and downstream activities on the overall results is observed. Finally, the inventory results are assigned to selected impact categories. Global warming (GWP), human toxicity (HTP), acidification (AP), photo-oxidant formation (POCP), eutrophication (EP), and primary energy demand are adopted as impact categories. The impact assessment indicates decreasing impacts for all categories with increasing combustion efficiency for the coal plants without carbon capture. As expected, the GWP for the MEA plants is much lower than for the power plants without CO_2 capture. In contrast to this, the HTP and the EP are much higher (up to three times) for the MEA plants. Sensitivity analysis reveals that the origin of coal and the

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corresponding transport distances have a significant impact on the overall results. Furthermore, it is concluded from the sensitivity analysis that for CCS systems the length of CO_2 pipeline has a negligible effect in comparison with the effect of capture efficiency. The LCA is completed by a normalisation of the environmental impact categories.

Discussion The development of combustion efficiency in case of the power plants without CO_2 capture has the main influence on the decreasing mass flows at the input side. The energy penalty of the MEA plants affects the use of the inputs into the opposite direction. Although the power producer's focus is on the power plant, the sense of a life cycle assessment is an integrated environmental assessment of the full life cycle of a product (here 1 kWh) including up and downstream processes. Therefore, the inventory results are presented without and with up and downstream processes. The inventory analysis clearly shows the significant influence of the up and downstream processes on the overall emissions. This influence is higher for the MEA plants than for the power plants without capture. In case of CO_2 emissions, the significance of up and downstream processes is especially considerable (approx. 30%). Sensitivity analysis reveals that the origin of coal and the corresponding transport distances have a significant impact on the overall results.

Conclusions The results point out that the reduction of carbon dioxide emissions into the atmosphere is achieved at the expense of increasing other emissions and corresponding environmental impacts. In most cases the influence of up and downstream processes is significant. Therefore, life cycle approaches are necessary to get a holistic evaluation. It also shows that the implementation of new techniques can change the environmental assessment of the process chain and, thus, positive and negative effects have to be compared and weighed up against each other.

Perspectives As there exist several possible technical options for CO_2 capture, further studies are necessary to compare the overall environmental effects of competing capture concepts such as pre-combustion and oxyfuel technology. Additionally, gas separating membranes should be part of further studies as they have the potential to contribute to all three main capture technology routes. Further studies with more detail and reliable inventories for CO_2 compression and liquefaction as well as for gas conditioning as an interface between CO_2 capture and transport are needed. Furthermore, the environmental effects including long-term CO_2 emission from the storage sites are recommended.

Keywords Carbon capture and storage (CCS) · Coal · Electricity generation · CO_2 emissions · Life cycle assessment (LCA) · Mono-ethanolamine (MEA) · Post-combustion · Power plant · Retrofit

1 Background, aim, and scope

One of the most important sources of global anthropogenic carbon dioxide emissions is the combustion of fossil fuels for power generation. Power plants contribute more than 40% of the worldwide anthropogenic CO_2 emissions and more than 24% of total GHG emissions (Stern 2006). Scenarios about the future global energy requirements forecast an increasing demand for electricity, which in 2030 is predicted to be twice the current demand (World Energy Outlook 2006). They also indicate that this increase can only be met by considerable use of coal, natural gas and oil, which will contribute to more than 70% of future electricity generation. As a consequence, the emissions of CO_2 will increase in accordance with increasing use of fossil resources unless appropriate measures are taken up to mitigate CO_2.

In the short and medium terms, a significant increase in power plant efficiencies will contribute to reduce specific CO_2 emissions. Additionally, for further reduction, as proposed by EU and member countries, a significant contribution of CCS is required, especially for fossil fuel power plants, which are by far the biggest point sources of CO_2 emissions. The option of capturing CO_2 and storing it allows the utilization of fossil fuel reserves with less CO_2 emissions. Recently, the concept of CCS as a means for reducing CO_2 emissions from power plants has emerged with several projects planned worldwide (IPCC 2005).

Although commercial technology exists to separate and capture CO_2 generated in large-scale industrial processes, applications are mainly found in the petroleum and petrochemical industries (particularly in the field of natural gas processing and ammonia production). Capture of CO_2 from combustion-generated flue gases has been demonstrated commercially only at small scale for gas-fired and coal-fired boilers (Rao and Rubin 2002). However, great efforts are necessary in R&D (optimisation, scaling up, process integration) to apply such technology on a large scale at power plants. In particular, the application of carbon capture technology in power plants demands handling of large volumes of flue gas with low CO_2 concentration, which at present is not commercially available. Therefore, an extensive deployment of fossil fuel power plants with CCS techniques is not expected before 2020. As a precondition, the ZEP Initiative (European Technology Platform for Zero Emission Fossil Fuel Power Plants) as well as the European Union and member countries (e.g. Germany, UK) plead for 10–12 full demonstration plants in Europe.

Carbon capture is an energy-intensive process, which lowers the overall efficiency of the power plant. In order to compensate for this efficiency loss, additional fuel input per unit of electrical output must be used, leading to additional emissions. Furthermore, while capturing CO_2 from the power plant reduces direct CO_2 emissions from the power plant

itself, upstream emissions resulting from fuel and materials supply and downstream emissions resulting from waste disposal and waste water treatment cannot be captured. Some of these upstream and downstream emissions are small when compared with direct emissions from combustion (e.g. ammonia). However, some of these emissions are dominant in comparison with the direct emissions of the combustion. In particular, the coal upstream processes are very important for methane and sulphur dioxide emissions, for example. When carbon capture is included, these emissions become more dominant due to the additional fuel utilization. So the high energy penalty associated with the corresponding emissions could form the main obstacle for carbon capture. Therefore, a life cycle assessment is required as an adequate method for a broad evaluation of environmental effects of a new technology route.

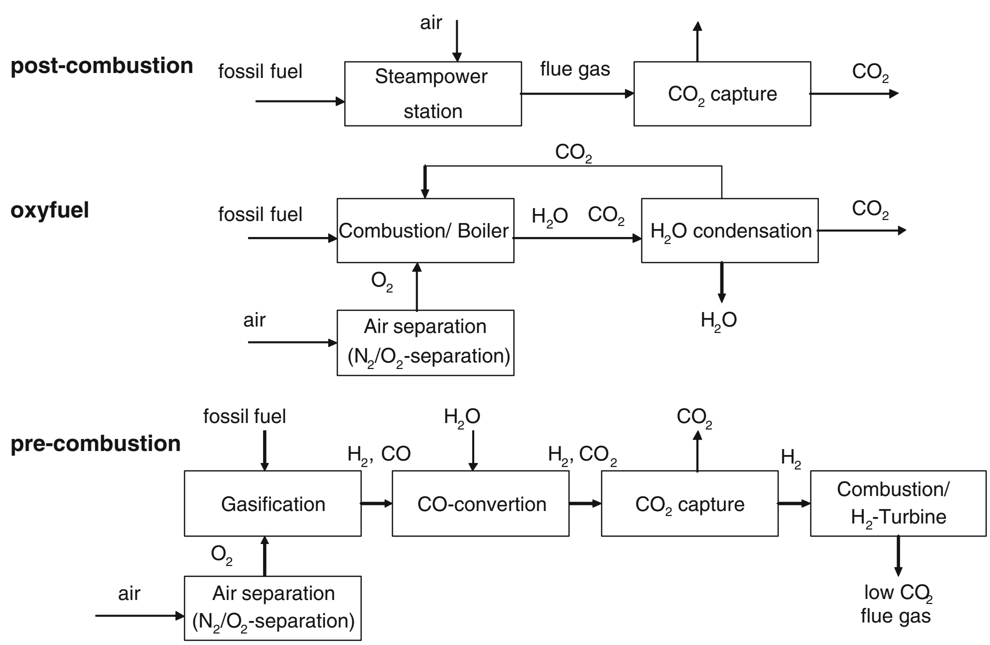
Although several environmental studies of future energy systems (often with CCS) have been published in recent years (Bauer et al. 2004; Dones et al. 2005; Fischedick et al. 2007; Hondo 2005; Markewitz et al. 2009; Odeh and Cockerill 2008; Pehnt 2003; Rubin et al. 2007; Ruether 2004; Schreiber et al. 2007; Thitakamol et al. 2007; Tzimas et al. 2007; Waku et al. 1995; Weisser 2007), which are partly based on life cycle assessment methodology, the environmental assessment of CCS is just at the beginning. In light of these considerations, the current paper investigates the environmental effects of five supercritical, pulverized coal-based steam power plants, which differ in the year of installation (2005, 2010, 2020), the conversion efficiency, and in the ability and efficiency to capture CO_2. For the analyses, post-combustion capture using MEA wash was chosen due to the highest level of maturity among the capture technologies. Analysis is conducted for each of the three power plants without capture and the two power plants with capture, and the results are compared among each other. In the analyses, high regard was paid to the influence of the upstream and downstream processes on the overall results. The life cycle inventory (LCI) results are assigned to six selected impact categories, and these are normalized. Finally, sensitivity analysis is undertaken to investigate the effects of some key parameters on the total impact results.

2 Description of CO_2 capture technology

In principle there are 3 main technology routes, which offer removal of CO_2 from combustion and gasification processes (Fig. 1):

1. Pre-combustion technology with subsequent CO-shift reaction results in formation of CO_2 and H_2. If H_2 can be continuously removed from the gas mixture, CO_2 can be easily separated and stored. Hydrogen can be used for electricity generation in gas turbines or for production of synthetic fuels or chemicals.
2. Oxyfuel combustion systems use oxygen instead of air for combustion, resulting in formation of CO_2 enriched flue gas and water as combustion products. Water can easily be separated from the combustion gas by condensation at low temperatures. For that, large air separation facilities are required.
3. For post-combustion separation CO_2 is removed after the combustion process e.g. by chemical treatment of the flue gas using amines. As the power generation process remains unchanged, this affords handling of large flue gas volumes with low CO_2 content.

Fig. 1 Technological concepts of CO_2 capture in power plants (Linssen and Markewitz 2007)



The technology routes have reached different levels of maturity (IPCC 2005). As post-combustion separation shows the farthest development, this study concentrates on this route, focusing on capture using MEA. Until 2020, replacement and capacity increase are announced for fossil fuel power plants, for which carbon capture by post-combustion retrofit might be an attractive mid-term option. This CO_2 capture method is a classical end-of-pipe solution based on gas separation technique using MEA as chemical absorption. Figure 2 shows the main process steps of a power plant including CO_2 capture using MEA wash and CO_2 compression.

After desulphurisation, the flue gas containing CO_2 and the MEA solution circulates at counter flow in the absorber. The flue gas is cleaned due to the strong chemical reaction between CO_2 and MEA. Afterwards, the MEA solution containing CO_2 is carried to a regenerator. In the regenerator the CO_2 is recovered through heating by low pressure steam. Subsequently, the MEA solution is re-treated by filtration, adsorption and, if necessary, by refilling. After that, the MEA solution is reused. The low pressure steam used for regeneration of MEA solution is taken from the steam power process and is no longer available for electricity generation. Accordingly, the power output of the steam turbine and the electricity yield decrease. After MEA wash, the separated carbon dioxide has to be liquefied by compression for further transport and storage.

The main advantage of retrofit is that the conventional combustion process remains mainly unchanged. However, from an environmental point of view, amine-based carbon capture has some drawbacks, which make an environmental assessment essential:

(a) Due to the high energy demand for separating CO_2 from the flue gas, the net efficiency of the power plant decreases up to 14 percentage points. Accordingly,

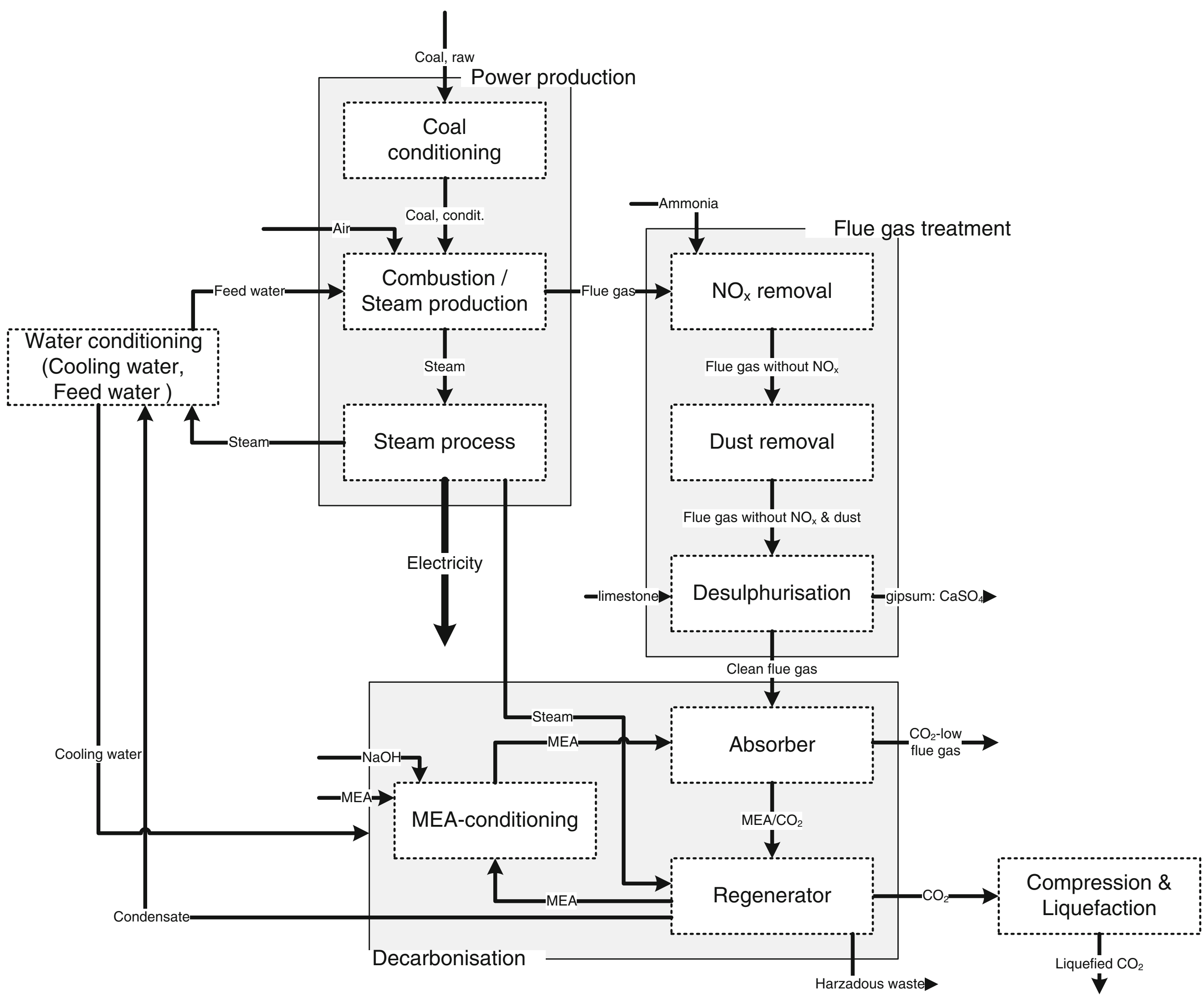


Fig. 2 Main process steps of a coal-based power plant including MEA wash

primary energy demand increases as well as all other raw materials and operating supplies like water, ammonia and limestone, which are necessary for the standard operation of flue gas treatment.

(b) There is a loss of MEA solution which is caused by irreversible interactions of flue gas components, oxidation, polymerisation and evaporation, and which has to be compensated by new MEA solution. Moreover, contaminated MEA solution has to be handled as hazardous waste.

(c) Up and downstream processes for additional material supply and waste management result in further energy demand and increasing raw materials and operating supplies.

In total, this results in increasing amounts of already inevitable inputs (e.g. raw coal) and outputs (e.g. waste water, gypsum) as well as new outputs (e.g. ethylene-oxide, hazardous wastes, for example degradation products of MEA, and additives), for which the environmental impacts have to be assessed.

3 Methodology

Environmental and human health impacts of electricity generation from pulverized coal-based power plants without CO_2 capture are compared with those with CO_2 capture. LCA is used as the evaluation tool which conforms to ISO 14040 / 14044 (ISO 2006). In the following sections, each phase of LCA adopted in this study is explained.

3.1 Goal and scope definition

3.1.1 Goal

Goal of this study is the comparison of the environmental and human health impacts of electricity generation from pulverized coal-based power plants without CO_2 capture and those with CO_2 capture over their entire life cycles, in order to identify the processes with the largest environmental impacts. Furthermore, the study examines the influence of the up and downstream processes on the overall inventory and impact results of the power plants.

3.1.2 System definition and boundaries

Adopting the ISO 14040 / 14044 guidelines, the system boundary is defined in a spatial, temporal, and technological context. The study examines the power generation of five pulverized coal-based steam power plants, which differ in the year of installation, the conversion efficiency, and in the ability and efficiency to capture CO_2. The plants are characterized either by performance data from existing coal power plants or experts' expectations for the years 2010 and 2020 in Germany.

(a) Coal plant$_{2005}$: Pulverized coal power plant already installed in the 90^{ies}, but operating still in 2005, no capture
(b) Coal plant$_{2010}$: Pulverized coal power plant installed in 2010, no capture
(c) Coal plant$_{2020}$: Pulverized coal power plant installed in 2020, no capture
(d) MEA$_{retrofit}$: Pulverized coal power plant installed in 2010 and retrofitted by MEA wash in 2020
(e) MEA$_{greenfield}$: Pulverized coal power plant with integrated MEA wash installed in 2020

Coal plant$_{2005}$ is the reference plant. For case (a)–(c) no capture components are assumed, but net conversion efficiency is expected to increase from 43% to 49% (Table 1). The advancement in case of (c) will be achieved by raising steam temperature up to 700°C as well as other optimization measures. Case (d) is a power plant installed in 2010 and retrofitted by amine-based carbon capture technique in 2020. The energy penalty is 10.5 percentage points, resulting in a net efficiency of 35.5%. Finally, case (e) is an integrated power plant with CO_2 capture which will be newly installed in 2020. The energy penalty is expected to be less, although it still is 7.5 percentage points, which results in a net efficiency of 41.5%. The reduction of energy penalty for MEA$_{greenfield}$ is reached by a better utilisation of steam energy due to an improvement in connecting facilities between combustion and capture technology. For both capture processes the CO_2 capture rate is 90%. The capture rate denotes the share of CO_2 which is captured from total CO_2 produced during combustion. Currently, retrofitting of a power plant installed in 2005 or even earlier with a MEA wash in 2020 appears unlikely.

Table 1 presents important performance and flue gas parameters of the power plants, which especially influence the environmental assessment. The SO_2 concentration will be reduced from 150 mg/m^3 for cases (a)–(d) to 29 mg/m^3 for MEA$_{greenfield}$. Hence, degradation of the MEA solution is reduced (Rubin et al. 2007; Tzimas et al. 2007). This reduction can be achieved by either a new, fully developed SO_2 removal technique or by increased input of limestone. In this study, the latter is assumed (2% more limestone). Additionally, it is assumed that the power plants meet the emission threshold values according to German BImSchV (BImSchV 2004), which distinguishes new from old plants.

For a comparative ecological inventory of the five coal power plants, material and energy balances on the level of

Table 1 Technical parameters of the power plants

	unit	Coal plant$_{2005}$	Coal plant$_{2010}$	Coal plant$_{2020}$	MEA$_{retrofit}$	MEA$_{greenfield}$
Plant parameters						
combustion capacity	MW_{th}	1164.0	1200.0	1423.5	1200.0	1423.5
net capacity	MW_{el}	500.5	552.0	697.0	426.5	592.0
net efficiency	%	43.0	46.0	49.0	35.5	41.5
energy penalty	%points	——	——	——	10.5	7.5
Flue gas parameters after flue gas desulphurisation						
sulphur dioxide concentration	mg/m³	150	150	150	150	29
nitrogen oxide concentration	mg/m³	185	185	185	185	185
particles	mg/m³	20	20	20	20	20
CO_2 capture parameters						
purity of CO_2	%				99	99
capture rate	%				90	90
MEA concentration	mass%				30	30

single processes, as well as for the whole process chains, are calculated using the environmental calculation software GaBi 4.2. The single process modules used describe techniques in Germany or in Europe. The process chains of the power plants without CO_2 capture (a)–(c) comprise “Coal conditioning”, “Power generation”, “NO_x removal”, “Dust removal”, “Desulphurisation” and up and downstream activities like the supply of raw coal and raw material as well as production of operating supplies and handling of solid waste (landfill processes) and emissions into water (Fig. 3). The process chains of the MEA plants (d, e) additionally include “Decarbonisation” and “Compression & Liquefaction” (Fig. 3). Construction and deconstruction of components of the power plants and capture facilities as well as service activities, which are not process-related (e.g. offices, canteen), are not included. With a lack of sound data for transportation and storage, inputs and outputs for these processes can only be estimated and therefore are excluded also from basic investigations. Nevertheless, the degree of its significance is demonstrated in the sensitivity analysis.

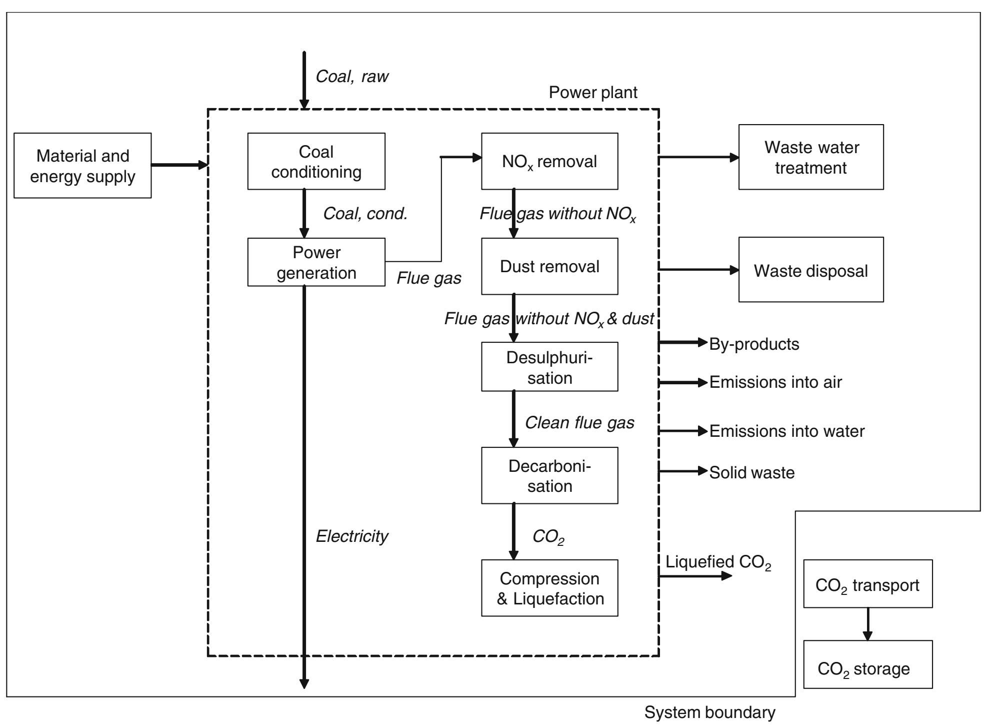


Fig. 3 System boundary for a power plant including MEA-based carbon capture

For “Power generation”, the inputs are raw coal, air and light fuel oil. The combustion process is calculated with coal Pittsburgh No. 8 for power plants in 2005 and 2010/2020, respectively. Nevertheless, for up and downstream processes, coal origin is represented by a mixed data set of various imports from the ecoinvent 1.3 database. The “NO_x removal” is carried out through NO_x wash using ammonia. The “Dust removal” is arranged by electrical precipitator. The “Desulphurisation” is accomplished through SO_2 wash using limestone. “Decarbonisation” is based on MEA wash, for which MEA solution is used. The chemicals (oxygen scavengers, corrosion inhibitors, antifoams) for stabilising the MEA solution are not included due to the lack of information. For “Compression” of CO_2, a multi-stage process with an intermediate cooling system is assumed (Göttlicher 1999).

3.1.3 Functional unit and allocation procedure

For the purpose of comparison, a fixed reference point for the environmental evaluation, the functional unit, is defined as 1 kWh net electricity produced (1 kWh_{el}).

Allocation may be necessary when a process yields more than one product, i.e. a multifunctional process. Although in case of the MEA plants a second product (namely CO_2) is produced deliberately (not for use, but for storage), in addition to electricity, no allocation procedures were carried out in this study. In the case of power plants with CO_2 capture, the separated CO_2 could be considered a product rather than an emission, because CO_2 holds an economic value according to CO_2 emission allowances or CO_2 tax systems. Nevertheless, no allocation procedure was performed in this study, because the CO_2 emission trading system is still in an early stage with volatile prices on the market for CO_2 emission allowances in Germany. For the interpretation of the results, this has to be considered.

3.2 Data collection for inventory analysis

The inventory data of the power plants used in this study are representative of the period between 1990 and 2020 for Germany. Whenever possible, typical process-specific data were collected for the single process modules. Otherwise average data from literature were used. Power plant parameters for 2005 were received from existing coal power plants in Germany. The data for 2010 are taken from publicly available literature for power plants under construction. Plant parameters for 2020 are estimated by means of expert’s assumptions. The remaining data (up and downstream processes) were obtained from the ecoinvent 1.3 database.

3.3 Impact assessment

The results of the inventory are discussed and translated to contributions to selected environmental impact categories. A quantitative impact assessment was performed for six categories: Primary energy demand, global warming, human toxicity, acidification, photo-oxidant formation, and eutrophication. Characterisation of environmental impacts is based on CML 2001 (Guinée et al. 2002). The Normalisation step relates the results of the impact assessment to the total amount of the corresponding impact category in Germany. Finally, sensitivity analyses are undertaken to determine the effect of some important parameters on the total life cycle impacts.

4 Results and discussion

4.1 Inventory analysis results

The development of combustion efficiency has the main influence on the mass flows at the input side (Table 2). According to the efficiency increase from 43% to 49% in the case of the coal plants without CO_2 capture, the use of hard coal, ammonia and limestone decreases with the ratio of efficiencies. The energy penalty of the MEA plants affects the use of these inputs into the opposite direction. But again, with decreasing energy penalty (= increasing efficiency), the inputs decrease. For limestone for $MEA_{greenfield}$, the increase is slightly higher than given by the energy penalty. This is

Table 2 Selected inputs of the power plants with and without up and downstream processes

Inputs g/kWh_{el}	Coal $plant_{2005}$		Coal $plant_{2010}$		Coal $plant_{2020}$		$MEA_{retrofit}$		$MEA_{greenfield}$	
	a	b	a	b	a	b	a	b	a	b
coal	416	282	389	263	365	247	504	341	431	291
ammonia	0.63	0.63	0.58	0.56	0.54	0.54	0.75	0.75	0.64	0.64
limestone	23	23	22	22	20	20	28	28	24	24
MEA	0	0	0	0	0	0	2.10	2.10	1.13	1.13
NaOH	0	0	0	0	0	0	0.11	0.11	0.09	0.09

[a] with up and downstream processes; [b] without up and downstream processes

due to the additional limestone used to reduce SO_2 concentration in the flue gas to avoid high degradation of the MEA solution. The MEA solution is an additional input which is needed by the MEA plants. Comparing $MEA_{retrofit}$ and $MEA_{greenfield}$, it is reduced by approximately 50%. This is caused by two effects: There is less CO_2 to be captured per kWh and there is a reduction of the SO_2 concentration after FGD for $MEA_{greenfield}$.

Although the power producer's focus is on the power plant the sense of a life cycle assessment (accordingly ISO 2006) is an integrated environmental assessment of the full life cycle of a product (here 1 kWh) including up and downstream processes. Therefore, the inventory results in Tables 2 and 3 are presented without and with up and downstream processes. Table 2 shows no increase for the inputs (ammonia, limestone, MEA, sodium hydroxide), except for coal, since these materials are direct power plant inputs not affected by any upstream process.

For the outputs, a similar argumentation holds. As expected, due to the increase of combustion efficiency of the coal plants without capture, the results demonstrate a decrease of the CO_2 from 796 g/kWh$_{el}$ in 2005 to 686 g/kWh$_{el}$ in 2020 (about 14%, see Table 3). If Coal plant$_{2005}$ is compared with $MEA_{greenfield}$, CO_2 emissions will then be even reduced by 86 and 90%, with and without up and downstream processes, respectively. Comparing Coal plant$_{2020}$ with $MEA_{greenfield}$, CO_2 emissions will be reduced by 84 and 88%, with and without up and downstream processes, respectively (Table 3). On the one hand, according to efficiency increases in case of Coal plants$_{2005,\ 2010,\ 2020}$, the outputs of methane, sulphur dioxide, nitrogen oxide, ammonia, gypsum, heavy metals and waste decrease with the ratio of efficiencies (Table 3). On the other hand, in case of MEA plants, some emissions (like methane, NO_x) increase again according to the energy penalty (Table 3). For SO_2, ammonia, ethylene-oxide, gypsum and waste, the situation is different. The strong decrease of SO_2 and the strong increase of gypsum for $MEA_{greenfield}$ compared to coal plants are due to the necessary improvement of desulphurisation (additional limestone) if MEA wash is used. For $MEA_{retrofit}$, the decrease of SO_2 and the increase of gypsum are only caused by SO_2 bonding to MEA solution. The increase of ammonia for the MEA plants partly results from the upstream supply of MEA, but is mainly caused by the degradation of MEA. The ethylene oxide emissions results from MEA supply. The increased amounts of waste, particularly hazardous waste, arise from MEA residues. It has to be kept in mind that all results strongly depend on the coal quality, which is very different with respect to sulphur and carbon content (see Section 5).

The inventory analysis clearly shows the significant influence of the up and downstream processes on the overall emissions. This influence is still higher for the MEA plants than for the power plants without capture. In the case of CO_2 emissions, the significance of up and downstream processes is especially considerable as demonstrated in Fig. 4 for $MEA_{greenfield}$. In particular, the coal upstream processes (coal mining and transport) are relevant. Altogether, the CO_2 up and downstream emissions amount to approx. 30%.

The other emissions like SO_2, NO_x and NH_3 also increase with consideration of up and downstream processes (see Table 3). In case of heavy metal emissions into water and air the opposite is observable. These emissions are higher for the power plants without up and downstream processes, because the heavy metals are directly discharged in the waste water and in the waste without any treatment or disposal processes.

Table 3 Selected outputs of the power plants with and without up and downstream processes

Outputs g/kWh$_{el}$	**Coal plant$_{2005}$**		**Coal plant$_{2010}$**		**Coal plant$_{2020}$**		**$MEA_{retrofit}$**		**$MEA_{greenfield}$**	
	a	b	a	b	a	b	a	b	a	b
CO_2	796	769	731	706	686	662	135	95	113	81
methane	3.02	0	2.83	0	2.66	0	3.67	0	3.14	0
sulphur dioxide	0.64	0.47	0.59	0.43	0.55	0.40	0.30	0.07	0.25	0.06
nitrogen oxides	0.78	0.54	0.72	0.49	0.67	0.46	0.93	0.62	0.79	0.53
ammonia	0.01	0	0.01	0	0.01	0	0.19	0.17	0.16	0.15
ethylene-oxide (sum)	0.0	0	0.0	0	0.0	0	0.0065	0	0.0035	0
heavy metal (sum)	0.01	2.54	0.01	2.38	0.01	2.23	0.02	3.07	0.02	2.66
gypsum	39.6		37.0		34.8		47.9		41.9	
municipal waste	0.90		0.85		0.79		1.15		1.01	
hazardous waste	0.040		0.036		0.036		3.12		1.66	

[a] with up and downstream processes; [b] without up and downstream processes

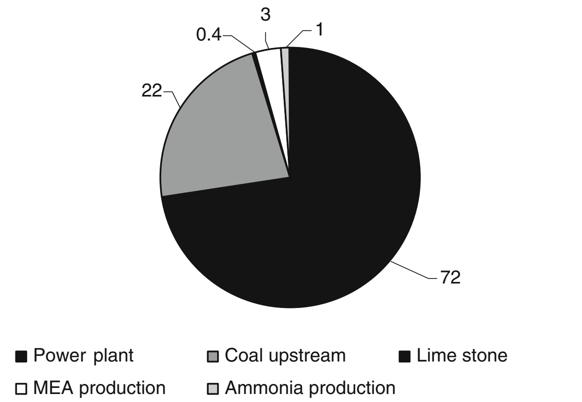


Fig. 4 Shares of CO_2 (%), emitted along the process chain of $MEA_{greenfield}$

4.2 Impact assessment results

4.2.1 Impact categories

Similar to the interpretation of the inventory results all six impact categories reduce with the increase of combustion efficiency for the coal plants without CO_2 capture. For the MEA plants, the energy penalty, resulting in additional already inevitable inputs and outputs, and new inputs as well as new outputs, affect the environmental impacts into different directions. As expected, the GWP for the MEA plants is much lower than for concepts without CO_2 capture and is lowest for $MEA_{greenfield}$ (Fig. 5).

In contrast to the global warming potential, the results for the other impact categories show different effects. For acidification potential and photochemical potential, the results for the five concepts are in the same range, but with a slight disadvantage for MEA plants in case of acidification and a slight advantage for $MEA_{greenfield}$ in case of photochemical potential. With respect to eutrophication and human toxicological potential, there are clear advantages for coal plants without capture. The results can be summarised as follows:

- For the MEA plants, up and downstream processes are significant for the *greenhouse gas potential*, mainly because of methane emissions due to additional coal extraction and coal transports.
- With respect to *acidification potential*, the MEA plants show slightly higher figures than coal $plant_{2010,\ 2020}$, although sulphur dioxide emissions are lower. This is due to the increase of ammonia output. For MEA plants, up and downstream processes are more significant than for coal plants without capture.
- In case of *eutrophication potential* coal plants (a)–(c) are less environmental harmful than MEA plants. This is mainly due to the increasing emissions of methane, ammonia and nitrogen oxides into the air for the MEA plants (decreased net efficiency). The contribution of up and downstream processes is significant.
- With respect to *photochemical oxidation potential* for all concepts, up and downstream processes are highly significant, with the highest significance for MEA plants. The high share of up and downstream processes are due to the hard coal supply chain with the corresponding emissions like methane, sulphur dioxide, nitrogen oxides and carbon monoxide.
- Up and downstream processes are clearly responsible for the bad evaluation of MEA plants for *human toxicological potential*. The high toxicological potential of the MEA plants predominantly follows from two aspects: firstly, heavy metals and organic emissions into air and water, mainly ethylene oxide emissions from the MEA supply, and secondly, heavy metals and some other long-term emissions into water from land filling of hazardous waste.
- With respect to *primary energy demand* the MEA plants show considerably higher figures than the reference plants due to the additional energy demand for CO_2 capture facilities. For all five power plant concepts, the up and downstream processes amount to approx. 28%.

4.2.2 Normalization results

The normalization is necessary to be able to compare the different environmental impact categories, because of their different units. The total amount of emissions in Germany in 2001 provides the basis for the normalization step. Of course the normalization results show the same tendency as the impact results (Fig. 6).

As expected, the normalized global warming impacts exhibit the highest values in the range between $7.12*10^{-13}$ (Coal $plant_{2005}$) and $1.53*10^{-13}$ ($MEA_{greenfield}$) followed by the acidification impacts levelled off around $2*10^{-13}$. All other normalized impacts settle down between $3.07*10^{-14}$ and $8.52*10^{-14}$, with a single exception of normalized HTP of $MEA_{retrofit}$ ($1.04*10^{-13}$). The Normalisation step points out for all power plants analysed, that no impact category leaves the order of magnitude between 10^{-13} and 10^{-14}.

5 Sensitivity analysis

Sensitivity analyses are undertaken with respect to 4 parameters to determine the effect on the total life cycle impacts (Table 4). The MEA plants were chosen as an example for the sensitivity analyses. Each parameter was separately varied.

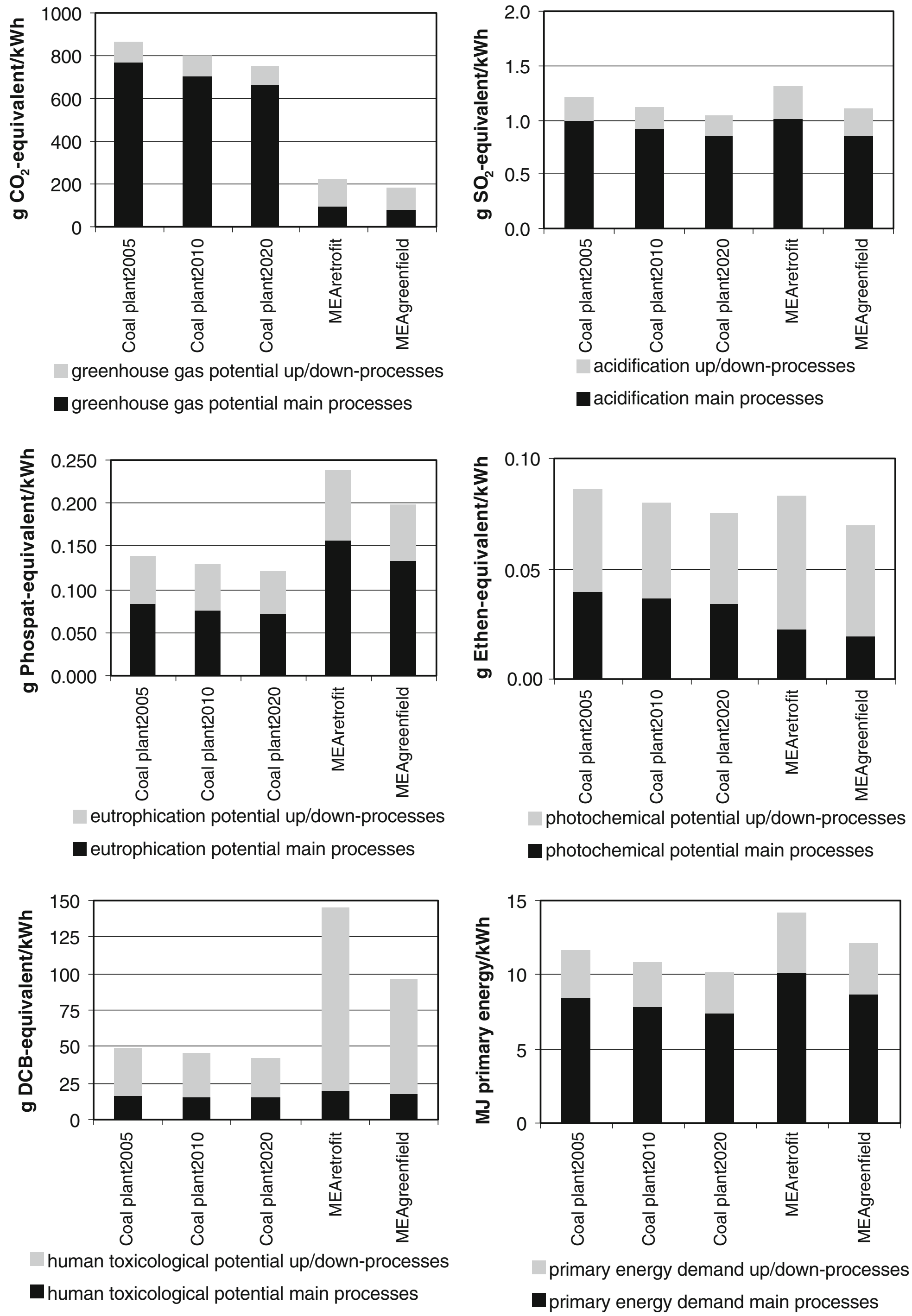


Fig. 5 Impact categories of power plants with and without up and downstream processes

5.1 Coal origin

As coal origin in the reference case the German hard coal mix is assumed. For variations, Western Europe, Australia, South Africa, and Russia are chosen. In our calculation, the origins do not affect the coal quality for combustion which is assumed to be Pittsburgh No. 8 for all the analyses, but it affects the supply of raw coal, which depends on the upstream processes “mining” and “coal transport”. The influence of the origin of imported coals on the life cycle impact results is shown in Fig. 7.

For the selected origins, inventories for extraction and for transports are very different. If the coal exclusively originates from Australia (AUS) or South Africa (ZA) all impact potentials increase except greenhouse gas potential due to the energy consumption of the long-distance trans-

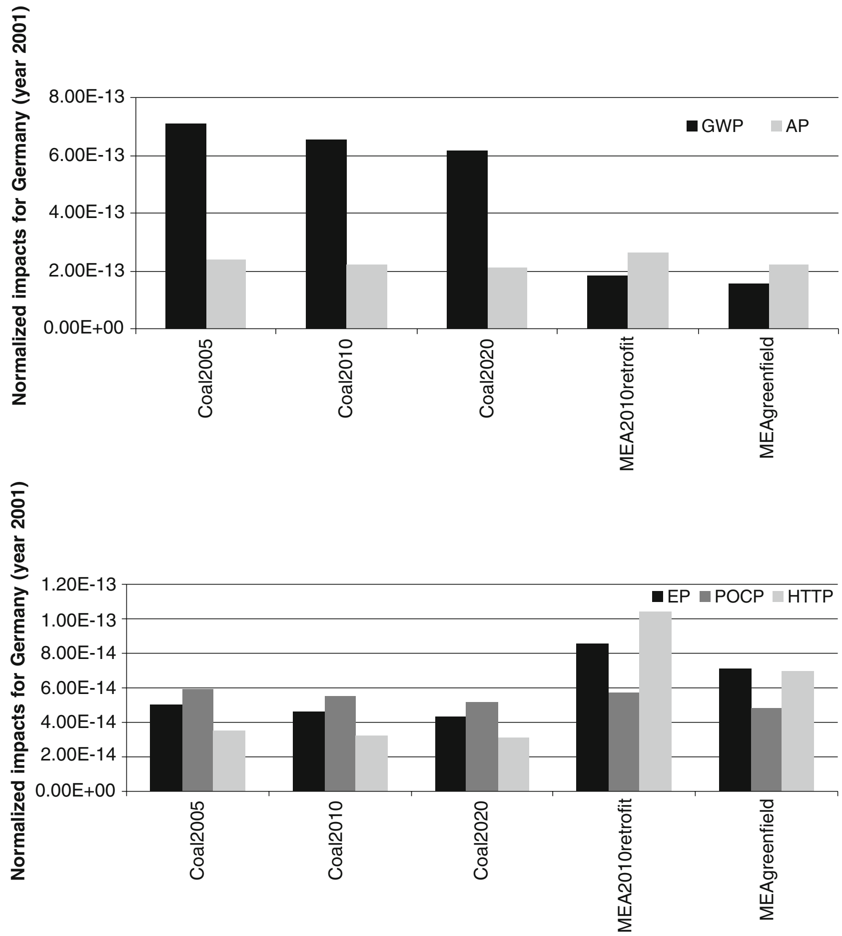


Fig. 6 Normalized impact categories for Germany in 2001 (CML method)

ports (diesel fuel for ships). The slight decrease for greenhouse gas potential is caused by much lower methane emissions during the extraction of coal in Australia and South Africa. If Western European or Russian coal is used, only marginal alteration is observed. Therefore, if a chosen technology needs higher coal inputs, the coal origin with its necessary transports is gaining increasing importance.

5.2 Transport and storage

For transport and storage of CO_2, process information is hardly available. Therefore, the calculations rest on two assumptions: For CO_2 pipeline transport, a module for natural gas transport from the ecoinvent 1.3 database is used. An average transport distance of about 300 km for CO_2 pipeline transport in Germany is assumed. For CO_2 storage, 50% of the life cycle inventory data from the pipeline transport is taken as a first estimation (Fischedick et al. 2007). Storage leakages are not accounted for. The results show an influence for greenhouse gas potential and acidification potential (Fig. 8).

For eutrophication and photochemical potential, a smaller influence is calculated. In both cases, $MEA_{greenfield}$ is superior. The increases mainly result from additional

Table 4 Parameters of the sensitivity analyses

Parameter	Reference case	Variation
Hard coal origin	German hard coal mix	Western Europe, Australia, South Africa, Russia
Inclusion of transport and storage	Without transport and storage	With transport and storage
Pipeline length	300 km	400 km
Absorbability of the MEA solution	0.25 mol CO_2/mol MEA	0.30 mol CO_2/mol MEA
		0.35 mol CO_2/mol MEA

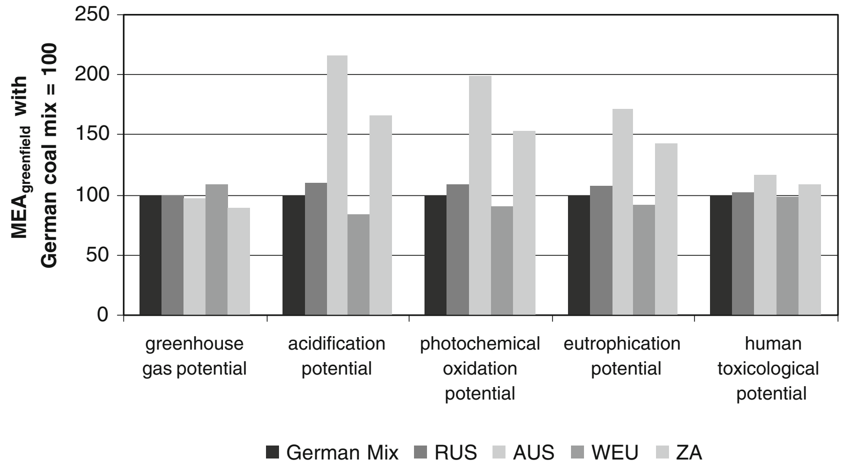


Fig. 7 Life cycle impacts of different coal origins (mining and transport) for $MEA_{greenfield}$

energy demand and methane emissions for (natural gas!) transport via pipelines. Nevertheless, effects on the overall results are small and have no influence on the comparison. Consequently, the extension of the CO_2 pipeline by 100 km has a negligible effect on the emissions, which correlates with other studies (Odeh and Cockerill 2007).

5.3 Absorbability of MEA

Currently, a lot of efforts are made to improve the absorbability of CO_2 absorbers, like amines, with the objective of enhancement of efficiency. Therefore, in the sensitivity analysis the absorbability of MEA solution was enhanced from 0.25 up to 0.30 and even to 0.35 mol CO_2/mol MEA. This involves a slight increase of efficiency up to 0.5 and 0.85 percentage points, respectively. However, this variation is too low for a noticeable improvement in life cycle impact assessment.

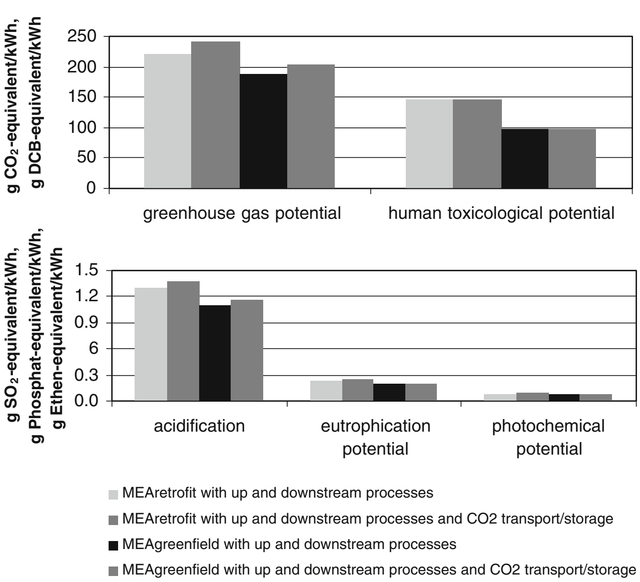


Fig. 8 Selected impact categories for the MEA plants including up and downstream processes as well as CO_2 transport and storage

6 Conclusions

The results point out that the reduction of carbon dioxide emissions to air by post-combustion carbon capture via MEA is achieved at the expense of increasing other emissions and corresponding environmental impacts. In most cases, the influence of corresponding up and downstream processes is significant. Therefore, life cycle approaches are necessary to get a holistic evaluation. It also shows that the implementation of new techniques can change the environmental assessment and positive and negative effects therefore have to be compared and weighed up against each other. Comparing integrated or retrofit options for MEA plants with the appropriate coal plant offer no clear overall advantage results for MEA-based carbon capture.

7 Perspectives

As several possible technical options for CO_2 capture exist, further studies are necessary to compare the overall environmental effects of competing capture concepts such as pre-combustion and oxyfuel technology. Additionally, gas separating membranes should be part of further studies as they have the potential to contribute to all three main CCS routes. Additionally, different CO_2 transport and, in particular, storage options (e.g. ship, pipeline, on-shore, off-shore storage) should be involved in further LCA studies to receive a full CCS process chain.

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